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Feasibility Study of Enhanced Combustion Via Improved Wood Stove Firebox Design

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16. ABSTRACT

The paper gives results of an examination of materials that might be used within the firebox of a wood-burning stove to produce more uniform and complete combustion. Although many materials were initially considered, refractory materials appear to possess the qualities desired relative to heat transfer, resistance to the firebox environment, availability, and cost. Further investigation of specific refractory materials has been carried out, resulting in a listing of material properties of potentially useful refractories and a determination of relative installed costs. Basic heat transfer calculations were used to determine the effects of the addition of refractory materials in the firebox. The use of refractory materials permitted an increase in stove inner wall temperatures and an increased cooldown time for a stove. The study showed that refractory materials could aid in maintaining internal firebox temperatures above the ignition temperatures of common emissions. This would not be a practical operational mode for an uninsulated stove. The study concluded that there is a need for actual testing to confirm the results cited in this study.

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Pollution	Pollution Control	13B
Stoves	Stationary Sources	13A
Wood	Wood Stoves	11L
Combustion Chambers		21B
Combustion Control		
Refractory Materials		11G

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FEASIBILITY STUDY OF ENHANCED COMBUSTION VIA IMPROVED WOOD STOVE FIREBOX DESIGN

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ABSTRACT

Emissions from incomplete combustion in wood burning stoves are becoming more of an environmental problem. In this study, materials were examined which might be used within the firebox of a wood burning stove to produce more uniform and complete combustion. Although many materials were initially considered, refractory materials appear to possess the qualities desired relative to heat transfer, resistance to the firebox environment, availability, and cost. Further investigation of specific refractory materials has been carried out, resulting in a listing of material properties of potentially useful refractories and a determination of relative installed costs. Basic heat transfer calculations were used to determine the effects of the addition of refractory materials in the firebox. The use of refractory materials permitted an increase in stove inner wall temperatures and an increased cooldown time for a stove. The results of this study show that refractory materials could aid in maintaining internal firebox temperatures above the ignition temperatures of common emissions. This would not be a practical operational mode for an uninsulated stove. This study also concludes that there is a need for actual testing to confirm the results cited in this study.

INTRODUCTION

The use of residential wood burning stoves has increased considerably in recent years. These stoves come in a very wide range of designs. As a consequence, combustion and resulting emissions, as affected by operational parameters, can vary widely between different stoves and even from the same stove. One possible design approach for reducing emissions is to place material inside the firebox that can lead to more complete combustion of the wood charge and any emission constituents present. Ideally any design modification should be essentially passive; i.e., requiring little or no attention by the user.

EXISTING STOVE DESIGNS

The design of existing residential wood stoves was reviewed to ascertain the various design and operational factors that affect wood stove emissions. The major design factors included: combustion chamber usage, drafting design, heat transfer mechanism(s), combustion controls, and materials of construction. The operational factors included: draft and flue adjustments, fuel type, and stove charging techniques. These design and operational factors are listed in Tables I and II, respectively.

Two observations about low-emission performance were derived from the review of existing stove designs. The primary activity in emission reductions in wood burning stove designs is the utilization of catalytic combustors. The design incorporation and after-market insertion of catalytic combustors is spurred by their relatively low cost and largely passive operation. The second observation concerns the good results that have been reported from emission tests of ceramic stoves.(1) While various wood stoves constructed from "mixed" materials (e.g., metal with stone inserts) are available, there does not seem to be an all ceramic wood stove currently in production in the United States.

RESISTANCE TO THE COMBUSTION PROCESS AND INCREASING COMBUSTION EFFICIENCY

A review of wood stove designs and operational parameters plus information concerning wood combustion provdes a range of process conditions for stove usage. The mechanical suitability of any material utilized within the firebox for emission reduction must be evaluated relative to the process conditions. These include: ranges of firebox temperatures, its heating and cooling rates, fuel constituents, and the products evolved during combustion. Table III lists the firebox temperatures and cooling rates assumed during this study. The combustion products considered are listed in Table IV.(2,3).

Any materials placed within the firebox must be resistant to the combustion process and should help enhance it, while not degrading stove

operation or requiring significant user attention. In the presence of sufficient oxygen, various emission constituents have defined ignition temperatures. Some of these ignition temperatures are presented in Table IV.(4,5) If a material within the firebox can be maintained at or above these ignition temperatures, combustion can take place and will lead to more complete reduction of emissions such as carbon monoxide and hydrocarbons.

CANDIDATE MATERIALS FOR INCLUSION IN THE FIREBOX

Various types of ceramics, refractories, insulating materials plus metallics and even consumable materials were considered as candidate materials for inclusion in a wood stove firebox. These materials were evaluated for their ability to resist the process environment and to enhance combustion, by the methodology described below. The generic types of materials surveyed are listed in Table V, together with comments about process resistance factors and the potential effects on combustion. Additional factors such as cost and ease of fabrication were considered during the evaluation of the various candidate materials. Table VI provides a listing of important material properties for refractory-type materials. All materials were assumed to be added within the firebox of a basic cast iron wood stove. Standard heat transfer calculation techniques were used to determine if a candidate material could enhance the combustion process.

Two examples of the heat transfer calculation methodology for the basic cast iron and a typical refractory lined stove are presented in Appendix A.(6,7) These calculations were done using a scientific calculator. A personal or larger computer could be used for greater efficiency and accuracy. The first example shows the calculations for the basic cast iron stove. An outside wall temperature of about 720 °F* was calculated for the basic stove. This temperature is used in the second example, the stove with refractory lining, to maintain an equivalent heating effect. It can be seen that a relatively thin section of common medium duty firebrick placed at the firebox wall can be maintained at a temperature during steady state operation that is above the ignition temperature of several common emission constituents. The brick lining will also increase the duration of useful heat output during stove cooldown; e.g., during overnight use (see Figure 1). Figure 2 shows the effects of various thicknesses of typical refractory type materials on stove inside wall temperatures. Auxiliary heat removal methods such as heat exchangers or fins were not considered.

For refractory lined stoves, an inside wall temperature of 1200 °F was selected (along with an outside wall temperature of 720°F) as an effective temperature relative to emission ignition temperatures. The required wall thicknesses of the various refractory materials were calculated based on these assumed temperatures. These wall thicknesses are presented in Table VII.

Metric/English conversion factors are given near the end of this paper, as Table IX.

Because of concerns about fouling and potential overheating, catalytic materials may only be practical at or downstream of the firebox exit. Due to the dependence/variability of combustor temperatures on process conditions, catalytic combustors were not amenable to the calculation methodology utilized, and were, therefore, not considered further in this study.

Depending on stove configuration, the retrofitting with refractory linings could be difficult. Composite firebox walls, consisting of more than two materials, have not been evaluated. The heat transfer calculation methodology would also be applicable to such designs.

RANKING OF CANDIDATE MATERIALS

There are a great many possible ways to rank the numerous candidate materials that exhibit suitable combustion resistance and offer a potential enhancement in combustion efficiency. Logically, the rating criteria of Total Installed Cost (TIC) per square foot would be of considerable interest to both wood stove manufacturers and owners. For a given material combination, the TIC for original manufacture could vary considerably from the cost (and practicality) of retrofit. The listing presented in Table VIII gives ratios of TIC's, for new fabrication, using several candidate materials, based on an assumed equivalent temperature profile for the stove wall. It should be noted that the utilization of these potential designs may not prove cost-effective compared to the installation of catalytic combustors. The installation of refractory linings may also lead to a higher consumption of fuel per hour.

Several of the castable materials show relatively low TIC's. These values do not, however, consider the potential negative appearance factors and possible cracking common in castable materials.

The light weight insulating bricks and light weight castable materials (densities below about 65 pounds per cubic foot) also have low TIC's. These materials are very good insulators; therefore, only very thin sections are required to attain a reasonable temperature profile. These insulating refractories are, however, also relatively soft materials. The combination of thin sections and limited strength would tend to make them prone to damage during fuel charging.

CONCLUSIONS

* Various types of refractory materials can be installed within a wood stove firebox which can lead to temperatures at and near the refractory surface that are above the ignition temperature of many wood stove emission constituents.

* A refractory lined stove will tend to have a longer cooldown period than a metal stove.

* A quantification of the effectiveness of emission reductions attributable to the types of firebox designs considered herein should be determined by various testing procedures.

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TABLE I. DESIGN FACTORS IN WOOD BURNING STOVES

COMBUSTION CHAMBER	DRAFTING	HEAT TRANSFER MECHANISM	COMBUSTION CONTROL	MATERIALS OF CONSTRUCTION
Primary Primary and secondary Catalytic Combinations of above	Down draft Up draft Cross draft Diagonal draft S flow draft Induced draft Forced draft	Radiator - direct radiation, convection, and conduction Circulators - heat exchangers Augmented - fans and blowers	Temperature probes Baffles Various air supplies (i.e., secondary air) Blowers or fans Manual damping Automatic damping	Ceramic Soapstone Steel Cast iron Firebrick Combinations of above

TABLE II. OPERATIONAL FACTORS IN WOOD BURNING STOVES

DRAFT AND FLUE ADJUSTMENTS	FUEL TYPE	STOVE CHARGING TECHNIQUES
Manual	Wood logs	Manual
Automatic	Wood chips	Automatic
Automatic	Wood pellets	Automatic
Automatic	Saw dust	Automatic
Manual	Kiln dried wood	Manual
Manual	Composite logs	Manual

TABLE III. ASSUMED FIREBED TEMPERATURES AND COOLING RATES USED FOR THE BASIC STOVE

Bed temperature at t = 0 hrs. :	1500 ^{o}F (815 ^{o}C)
Bed temperature at t = 7 hrs. :	200 ^{o}F (93 ^{o}C)
Equation for bed cooldown:	Temp. = $1500e^{-0.28\ time}$
Room temperature:	60 ^{o}F (16 ^{o}C)

For all stoves: initial outside wall temperature (t = 0): 720 ^{o}F (382^{o}C)
initial inner wall temperature (t = 0): 1200 ^{o}F (649 ^{o}C)

TABLE IV. SOME COMBUSTION PRODUCTS RESULTING FROM BURNING OF WOOD

COMBUSTION PRODUCTS	
Carbon monoxide[a]	
Sulfur dioxide	
Nitrogen oxide	
Naphthalene[b]	examples of POM's (polycyclic organic matter)
Anthracene	
Penanthrene	
Biphenyl[c]	
Fluoranthene	
Pyrene	
Chrysene	
Benzene[d]	

a. Ignition temperature 1128 °F (609 °C)

b. Ignition temperature 898-1017 °F (481 - 547 °C)

c. Ignition temperature 1071 °F (577 °C)

d. Ignition temperature 1097 °F (592 °C)

TABLE V. CANDIDATE MATERIALS

MATERIAL	COMMENTS
METALS	GENERAL: Very high heat conductivity, face temperatures may not promote combustion at or near surface.
Ferrous	
Steels/cast irons	Not resistant to peak bed temperatures.
Alloy steels	
Stainless steels	
Non-ferrous	
Aluminum alloys	Not resistant to peak bed temperatures.
Copper alloys	
Nickel/cobalt-based	Expensive.
Refractory metals (Mo, W, Cb, Ta)	Expensive.
Titanium alloys	Expensive.
Lead alloys	Not resistant to peak bed temperatures.
Magnesium alloys	Not resistant to peak bed temperatures.
Zinc alloys	Not resistant to peak bed temperatures.
Tin alloys	Not resistant to peak bed temperatures.
CERAMICS/REFRACTORIES	
Alumina	
Alumina/silica	
Silica	
Basic (MgO) (Cr_2O_3)	
Zirconia	Expensive.
Carbides/nitrides (SiC, B_4C, TiN)	Expensive.
Combustibles	Not resistant to process, not passive.
Catalytics	May overheat or foul in firebox environment.

TABLE VI. REFRACTORY MATERIAL PROPERTIES

MATERIAL (TRADENAME)	COMPOSITION (A/S/)		CONDUCTIVITY @ 1000° F	DENSITY lb/ft^3
BRICKS				
MDFB	34/59		0.65	127
HDFB A	39/56		0.75	136
HDFB B	45/52		1.33	139
Mullite	69/26		1.10	144
Alumina	90/10		1.90	183
Alumina	99+/-		2.63	196
Silica	-/96		0.81	115
Vitrified Silica	-/99		0.58	118
Basic	11/-	50 MgO 16 Cr_2O_3	1.75	193
Zircon	-/33	67 ZrO_2	1.47	235
Silicon Carbide	-/-	90 + SiC	10.17	166

(continued)

[NB: NOTES APPEAR AT END OF TABLE.]

TABLE VI. (continued)

MATERIAL (TRADENAME)	COMPOSITION (A/S/)		CONDUCTIVITY @ 1000° F	DENSITY lb/ft^3
BRICKS (cont.)				
K23 IFB	39/44		0.11	31
K26 IFB	40/55		0.18	46
K28 IFB	46/52		0.18	48
K30 IFB	46/52		0.20	51
K3000 IFB	64/34		0.20	58
Dense IFB	71/21		0.49	82
CASTABLES				
Visil (a)	17/71		0.38	118
Harchrome (a)	34/-	43 Cr_2O_3 17 MgO	0.58	156
Kaocrete B (b)	38/46		0.37	72
KS-4 (c)	42/40		0.34	72
Kast-set (c)	43/41		0.36	72

(continued)

[NB: NOTES APPEAR AT END OF TABLE.]

TABLE VI. (continued)

MATERIAL (TRADENAME)	COMPOSITION (A/S/)	CONDUCTIVITY @ 1000° F	DENSITY lb/ft^3
CASTABLES (cont.)			
HW Super Castable (a)	45/43	0.54	122
Kaocrete 28LI (b)	49/42	0.52	126
LW26 (a)	53/37	0.09	55
Hi Alumina (a)	62/30	0.67	139
Alusa (a)	73/21	0.86	149
Castolast G (a)	94/-	0.99	170

NOTES:

Composition A/S/ = Alumina (Al_2O_3) / Silica (SiO_2)
Conductivity units = Btu/hr ft °F
MDFB = Medium-duty firebrick
HDFB = Heavy-duty firebrick
IFB = Insulating firebrick

(a) Harbison Walker Company
(b) Babcock & Wilcox - Refractories Division
(c) A. P. Green Company

TABLE VII. CALCULATED WALL THICKNESS FOR ASSUMED DESIGN CONDITION OF 1200°F INSIDE WALL TEMPERATURE, 720°F OUTSIDE WALL TEMPERATURE FOR VARIOUS REFRACTORY MATERIALS

MATERIAL (TRADENAME)	WALL THICKNESS (inches)
BRICKS	
MDFB	1.0
K23 IFB	0.2
K26 IFB	0.3
K28 IFB	0.3
K30 IFB	0.3
Silica	1.3
HDFB A	1.1
K3000 IFB	0.3
HDFB B	1.9
Vitrified Silica	0.8
Mullite	1.6
Dense IFB	0.7
Basic (MgO)	2.5
Zircon	2.0
Alumina (90/10)	2.6
Alumina (99/-)	3.2
Silicon Carbide	12.5

(continued)

[NB: NOTES APPEAR AT END OF TABLE.]

TABLE VII. (continued)

MATERIAL (TRADENAME)	WALL THICKNESS (inches)
CASTABLES	
MDFB (brick basis)	1.0
LW26 (a)	0.1
Kaocrete B (b)	0.5
KS-4 (c)	0.5
Kast-set (c)	0.5
Kaocrete 28LI (b)	0.7
HW Super Castable (a)	0.8
Visil (a)	0.6
Harchrome (a)	0.8
Hi Alumina (a)	0.9
Alusa (a)	1.2
Castolast G (a)	1.3

NOTES:

(a) Harbison Walker Company.

(b) Babcock & Wilcox - Refractories Division.

(c) A. P. Green Company.

MDFB = Medium-duty firebrick.

IFB = Insulating firebrick.

HDFB = Heavy-duty firebrick.

TABLE VIII. TOTAL INSTALLED COST (TIC) PER SQUARE FOOT RATIOS FOR VARIOUS REFRACTORY MATERIALS

MATERIAL (TRADENAME)	TIC RATIO
BRICKS	
MDFB	1.0
K23 IFB	0.5
K26 IFB	1.0
K28 IFB	1.1
K30 IFB	1.3
Silica	1.4
HDFB A	1.5
K3000 IFB	1.7
HDFB B	5.4
Vitrified Silica	6.5
Mullite	8.8
Dense IFB	9.1
Basic (MgO)	9.4
Zircon	26.9
Alumina (90/10)	35.2
Alumina (99/-)	69.8
Silicon Carbide	438.5

(continued)

[NB: NOTES APPEAR AT END OF TABLE.]

TABLE VIII. (continued)

MATERIAL (TRADENAME)	TIC RATIO
CASTABLES	
MDFB (brick basis)	1.0
LW26 (a)	0.1
Kaocrete B (b)	0.5
KS-4 (c)	0.6
Kast-set (c)	0.6
Kaocrete 28LI (b)	0.9
HW Super Castable (a)	1.0
Visil (a)	1.4
Harchrome (a)	1.5
Hi Alumina (a)	1.8
Alusa (a)	2.7
Castolast G (a)	7.0

NOTES:

TIC Ratio = Ratio of total installed cost per square foot to MDFB.

(a) Harbison Walker Company.

(b) Babcock & Wilcox - Refractories Division.

(c) A. P. Green Company.

IFB = Insulating firebrick.

HDFB = Heavy-duty firebrick.

MDFB = Medium-duty firebrick.

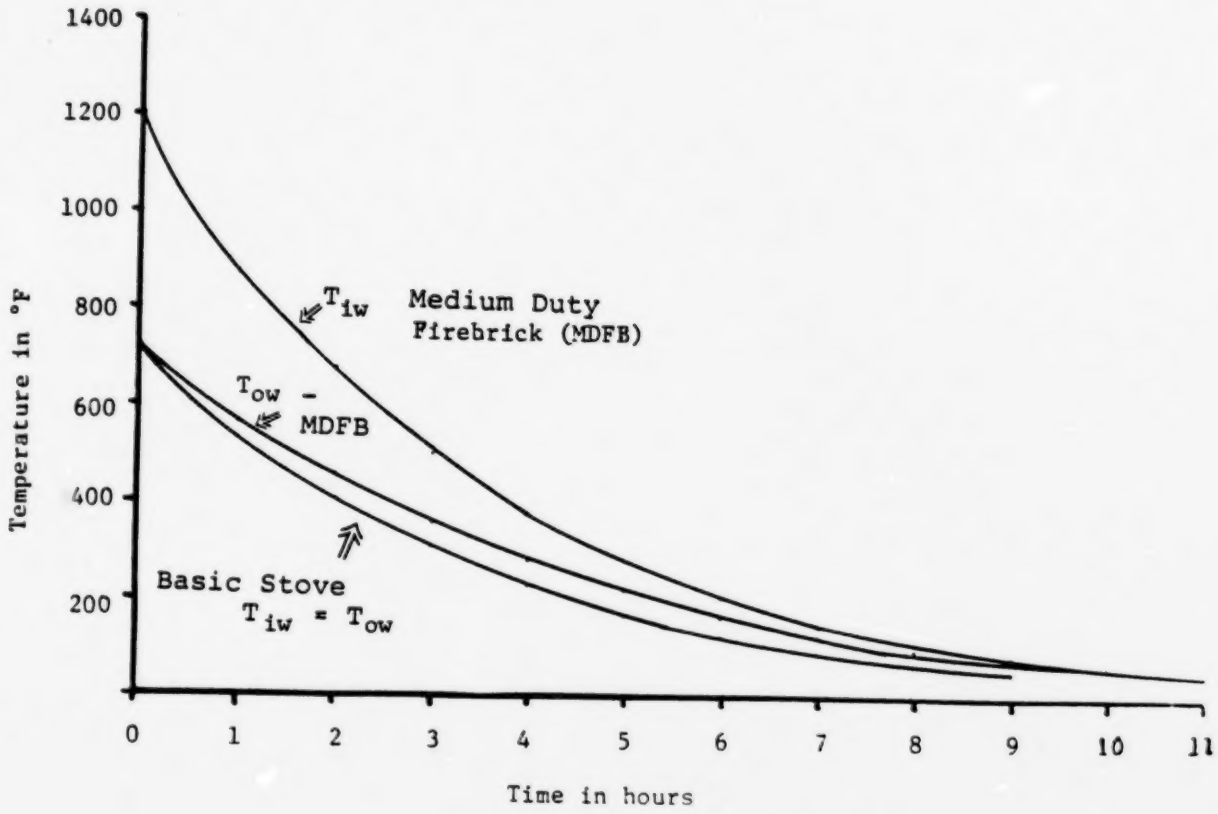

Figure 1. Cooldown of a basic wood burning stove (i.e., no insulation and 1/4 inch cast iron walls) and an insulated stove (1 inch of medium duty firebrick). For the basic stove, inner and outer wall temperatures vary by less than 5 ^{o}F so only a single curve is shown. The inner stove wall (T_{iw}) and outer stove wall (T_{ow}) temperatures are shown for the case of the insulated stove. Initial conditions were set such that the outer wall temperature of the basic stove and the insulated stove were the same.

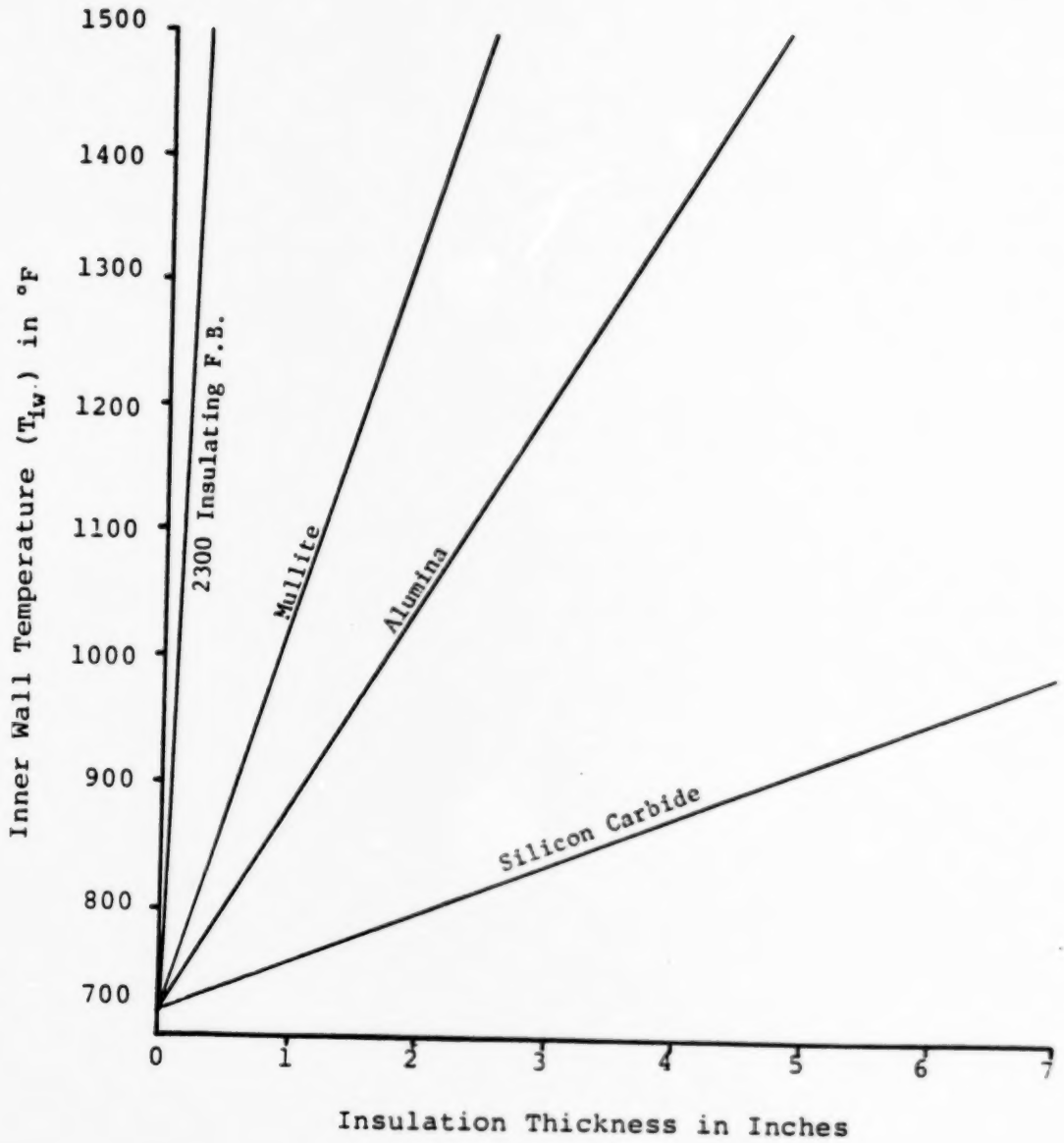

Figure 2. Inner wall temperature versus insulation thickness.

TABLE IX. METRIC/ENGLISH CONVERSION FACTORS

To convert from	To	Multiply by
Degrees Celsius (°C)	Degrees Fahrenheit (°F)	$t(°F) = 1.8\ t(°C) + 32$
Joule (J)	Btu	9.478×10^{-4}
Kilogram (kg)	Pound-mass (avoirdupois)	2.205
Kilojoule/kilogram (kJ/kg)	Btu/lb_m	4.299×10^{-1}
Megagram (Mg)	Ton (2000 lb_m)	1.102
Megawatt (MW)	Horsepower (HP)	1.341×10^{-3}
Meter (m)	Foot (ft)	3.281
Meter^3 (m^3)	Barrel (bbl)	6.290
Meter^3 (m^3)	Foot^3 (ft^3)	3.531×10^{1}
Meter^3 (m^3)	Gallon (gal)	2.642×10^{2}
Nanogram/joule (ng/J)	lb_m/million Btu	2.326×10^{-3}
Picogram/joule (pg/J)	lb_m/million Btu	2.326×10^{-6}

APPENDIX A

Two Samples of the Heat Transfer Calculation Methodology

Definition of terms for the following calculations:

Basic Stove:

t = time, hrs.

T_{fire} = temperature of firebox gases, °F or °R (°R = °F + 460)

T_w = temperature of basic stove wall, °F or °R

$(Q/A)_{fire}$ = heat transferred per square foot of stove wall from the firebox gases, Btu/hrft^2

σ = Stefan - Boltzman constant, Btu/hrft^2°R^4

ε_{fire} = emissivity of firebox gases

α_{fire} = absorptance of firebox gases

$\bar{h}_c$ = average convective conductance, Btu/hrft^2°F

$(Q/A)_{room}$ = heat transferred per square foot of stove wall to the room, Btu/hrft^2

ε = emissivity of cast iron

T_{room} = temperature of the room, °F or °R

Insulated Stove:

T_{iw} = temperature of inner stove wall (insulated wall - firebox side), °F or °R

T_{ow} = temperature of outer stove wall (cast iron - room side), °F or °R

t_{iw} = thickness of insulation, in.

t_{ow} = thickness of cast iron stove wall, in.

k_{iw} = thermal conductivity of insulation, Btu/hrft°F

k_{ow} = thermal conductivity of cast iron, Btu/hrft°F

σ = Stefan-Boltzman constant, Btu/hrft^2°R^4

ε_{fire} = emissivity of firebox gases

α_{fire} = absorptance of firebox gases

$\bar{h}_c$ = average convective conductance, Btu/hrft^2°F

T_{fire} = temperature of firebox gases, °F or °R

$(Q/A)_{fire}$ = heat transferred per square foot of stove wall from firebox gases, Btu/hrft^2

ρ = density of insulation, lb/ft^3

c = specific heat of insulation, Btu/lb°F

T_{av1} = average stove wall temperature (for entire wall, insulation and cast iron) at previous time step, °F

T_{av2} = average stove wall temperature at current time step, °F

$(Q/A)_{wall}$ = heat transferred (per square foot of stove wall) by conduction through the stove wall, Btu/hrft^2

$(Q/A)_{room}$ = heat transferred (per square foot of stove wall) to the room, Btu/hrft^2

ε = emissivity of cast iron

T_{room} = temperature of room, °F or °R

t = time, hr.

Assumptions

Basic Stove:

at t = 0, T_{fire} = 1500°F

at t = 0, T_w = 720°F

at t = 7, T_{fire} = 200°F

$\alpha = 0.171 \times 10^{-8}$ Btu/hrft^2°R^4 (constant)

$\bar{h}_c$ = 2 Btu/hrft^2°F (constant)

ε = 0.875 (constant)

T_{room} = 60°F (constant)

$T_{iw} = T_{ow} = T_w$

Insulated Stove:

at t = 0, T_{ow} = 720°F

at t = 0, T_{iw} = 1200°F

at t = 0, $Q/A_{room\text{-}insulated\ stove} = Q/A_{room\text{-}basic\ stove}$

k_{ow} = 24.8 Btu/hrft°F (constant)

α = 0.171 X 10^{-8} Btu/hrft^2°R^4 (constant)

$\bar{h}_c$ = 2 Btu/hrft^2°F (constant)

ϵ = 0.875 (constant)

T_{room} = 60°F (constant)

t_{ow} = 0.25 inch (constant)

Firebox gases, basic stove wall, and inner and outer insulated walls are assumed to cool exponentially; i.e., $T = C_1 e^{ct}$

Equations

Governing equations for basic stove:

Eq. 1 $(Q/A)_{fire} = \sigma (\epsilon_{fire} T_{fire}^4 - \alpha_{fire} T_w^4) + \bar{h}_c (T_{fire} - T_w)$

Eq. 2 $(Q/A)_{room} = \sigma\epsilon (T_w^4 - T_{room}^4) + \bar{h}_c (T_w - T_{room})$

Eq. 3 $(Q/A)_{fire} = (Q/A)_{room}$

Eq. 1 is the heat transferred from the firebox gases to the inner stove wall due to radiation (first term) and convective conductance (second term)

Eq. 2 is the heat transferred from the stove wall to the room due to radiation (first term) and convective conductance (second term)

Eq. 3 the heat transferred to the inner wall from the firebox is equal to the heat transferred from the outer wall to the room

Governing equations for insulated stove:

Eq. 4 $(Q/A)_{fire} = \alpha (\epsilon_{fire} T_{fire}^4 - \alpha_{fire} T_{iw}^4) + \bar{h}_c (T_{fire} - T_{iw}) + \rho c t_{iw} (T_{av1} - T_{av2})$

Eq. 5 $(Q/A)_{wall} = \dfrac{T_{iw} - T_{ow}}{(t/k)_{iw} + (t/k)_{ow}}$

Eq. 6 $(Q/A)_{room} = \sigma\epsilon (T_{ow}^4 - T_{room}^4) + \bar{h}_c (T_{ow} - T_{room})$

Eq. 7 $(Q/A)_{fire} = (Q/A)_{wall} = (Q/A)_{room}$

Eq. 4 is the heat transferred from the firebox gases to the inner stove wall due to radiation (first term), convective conductance (second term), and stored heat in the insulated wall (third term)

Eq. 5 is the heat transferred through the wall due to conduction

Eq. 6 is the heat transferred from the outer stove wall to the room due to radiation and convective conductance

Approach

1. Define firebox and basic stove conditions at time (0). Assume T_{fire} = 1500°F, and T_{room} = 60°F. Stove is cast iron, uninsulated and has 1/4-inch wall thickness. Iterating between Eq. 1 and Eq. 2, T_w and $(Q/A)_{fire} = (Q/A)_{room}$ are found, T_w = 720°F and Q/A = 4063 Btu/hrft^2.

2. Assume T_{ow} = 720°F is the desired outer wall temperature for an insulated stove at time (0), just as it was for the basic stove at time (0), and that the same heat transfer to the room is desired as with an uninsulated stove; i.e., Q/A = 4063 Btu/hrft^2. Assume also that at time (0) it is desired that the inner wall temperature be slightly above the temperature required to combust emission gases, so set T_{iw} = 1200°F. Using Eq. 5, the insulation thickness necessary to achieve these conditions can be found. For medium duty firebrick t_{iw} = 0.914 inch. Using Eq. 4, T_{fire} at time (0) can also be found (stored energy term is assumed 0) and is T_{fire} = 1765°F.

3. The steady-state, time (0) conditions for the firebox gases of the basic stove and the insulated stove have now been defined.

4. For cooldown conditions, the firebox gases of the basic stove and the insulated stove are assumed to cool according to the exponential equation of the form:

$$\text{Temp.} = C_1 e^{c\ \text{time}}$$

Using time (0) values found previously for the firebox gas temperatures under basic stove and insulated stove conditions along with estimated firebox gas temperatures at some later time, cooldown firebox gas temperature profiles can be generated. Using the firebox gas temperature profile, the corresponding wall temperatures can be found by iterating between Eq. 1 and Eq. 2 for the basic stove or Eq. 1, Eq. 2, and Eq. 3 for the insulated stove.

5. This method allows a basic stove and an insulated stove to be compared: both are initially under the same heat transfer to room conditions (i.e., $T_w = T_{ow} = 720°F$ and $Q/A = 4063$ Btu/hrft^2).

Error Factors

1.	$\bar{h}_c = 2$ Btu/hrft^2°F	is an estimate and may vary with temperature
2.	$\varepsilon = 0.875$	emissivity varies with temperature. For cast iron, only ranges of emissivity were available, so an averaged value was used and set constant.
3.	ε_{fire} & α_{fire}	emissivity and absorptance vary with firebox gas temperatures. Data for CO_2 and water vapor were used; however, data were in graphical format and, therefore, may introduce inaccuracies.
4.	k	thermal conductivity also varies with temperature. Again only ranges were available, so averaged values were used and set constant.
5.	T_{fire}, T_w	initial firebox gas temperature and stove wall temperatures were assumed. While literature supports these values, they are estimates.
6.	Temperature profiles	Again, these are estimates based on literature and experience.

The above error factors may appear cumbersome but the intent of these calculations is not to perfectly describe the heat transfer behavior of the wood burning stoves considered but rather to estimate the trends in the heat transfer behavior.

Error factors 1 through 4 could easily be handled by performing these calculations on a computer where tabular values would be stored and called upon for each iterative step.

Error factors 5 and 6 probably require actual testing to obtain better temperature values.

How does a basic stove cool when starting from T_{fire} = 1500°F and T_{wall} = 720°F?

Time t (hrs)	Fire Temp. T_{fire} (°F)	Temp. Stove Wall T_w (°F)
0	1500	(720°F)
1	1125	(545) 544
2	843	(410) 411
3	633	(305) 311
4	474	235
5	356	178
6	267	134
7	200	101

(Values in parentheses are calculated from iteration table below; other values are from exponential cooldown equation.)

$$(Q/A)_{fire} = \underbrace{\sigma\,(\varepsilon_{fire}\,T_{fire}^{4} - \alpha_{fire}\,T_w^{4})}_{\text{term 1}} + \underbrace{\bar{h}_c\,(T_{fire} - T_w)}_{\text{term 2}}$$

$$(Q/A)_{room} = \underbrace{\sigma\varepsilon\,(T_w^{4} - T_{room}^{4})}_{\text{term 1}} + \underbrace{\bar{h}_c\,(T_w - T_{room})}_{\text{term 2}}$$

		$(Q/A)_{fire}$				$(Q/A)_{room}$					
α_{fire}	T_w	term 1	+	term 2	= total	term 1	+	term 2	= total	T_{fire}	ε_{fire}
0.15	675	1085	+	900	= 1985	2374	+	1230	= 3604	1125	0.14
	600	1187	+	1050	= 2237	1780	+	1080	= 2860		
	550	1244	+	1150	= 2394	1448	+	980	= 2428		
	545	1249	+	1160	= 2409	1417	+	970	= 2387		
	at t = 2, T_{fire} = 843°F									843°F	0.15
0.18	375	590	+	936	= 1526	618	+	630	= 1248		
	425	550	+	586	= 1136	808	+	730	= 1538		
	400	571	+	886	= 1457	709	+	680	= 1389		
	410	563	+	866	= 1429	748	+	700	= 1448		
	405	567	+	876	= 1443	728	+	690	= 1418		
	at t = 3, T_{fire} = 633°F									633	0.15
	275	276	+	716	= 992	327	+	430	= 757		
	300	263	+	666	= 929	390	+	480	= 870		
	325	269	+	616	= 885	459	+	530	= 989		
	305	261	+	656	= 917	403	+	490	= 893		

Basic stove will cool down exponentially

$$T_w = C_1 e^{ct}$$

$C_1 = 720$ $C = -0.28$

Firebox will cool down:

$$T_{fire} = C_1 e^{ct}$$

where $T_{fire} = 1500°F$ at $t = 0$ hrs.

$T_{fire} = 200°F$ at $t = 7$ hrs.

$C_1 = 1500$ $C = -0.288$

Given: Medium duty firebrick with $k_{iw} = 0.65$ Btu/hrft°F

$\rho_{iw} = 127$ lb/ft^3

$T_{ow} = 720°F$, $T_{iw} = 1200°F$ } at $t = 0$

$Q/A = 4063$ Btu/hrft^2

What is the insulation thickness for these conditions?

$$Q/A = \frac{T_{iw} - T_{ow}}{(t/k)_{iw} + (t/k)_{ow}} = \frac{1200 - 720}{t/0.65 + \frac{0.25/12}{24.8}} = 4063$$

$\therefore t = \underline{0.914 \text{ inch}}$

What is the firebox temperature necessary for these conditions?

$$Q/A = \sigma (\varepsilon_{fire} T_{fire}^4 - \alpha_{fire} T_{iw}^4) + \bar{h}_c (T_{fire} - T_{iw})$$

$$4063 = 0.171 \times 10^{-8} (0.11 T_{fire}^4 - 0.13 \times 1660°R^4) + 2 (T_{fire} - 1200)$$

try $T_{fire} = 1600°F$

$4063 = 1699 + 800 = 2499$

try $T_{fire} = 1900°F$

$4063 = 4147 + 1400 = 5547$

try $T_{fire} = 1800°F$

$4063 = 3219 + 1200 = 4419$

try $T_{fire} = 1750°F$

$4063 = 2799 + 1100 = 3899$

try $T_{fire} = 1700°F$

$4063 = 2964 + 1140 = 4104$

try $T_{fire} = 1765°F$

$4063 = 2922 + 1130 = 4052$

Assume the firebox cools down exponentially

$$T_{fire} = C_1 e^{ct}$$

and reaches ~200°F in 8 hours

$\underline{C_1 = 1765}$ $\underline{C = -0.27}$

t (hrs)	T_{fire} (°F)	T_{iw} (°F)	T_{ow} (°F)
0	1765°F	(1200°F)	(720°F)
1	1347	(876) 898	(570)
2	1029	(677) 672	(465) 461
3	785	(506) 503	(365) 363
4	599	(380) 376	(285) 285
5	458	281	224
6	349	211	177
7	267	158	139
8	204	118	109
9	155	88	86
10	119	66	68
11	91		
12	69		

(Values in parentheses are calculated from iteration table on next page; other values are from exponential cooldown equation.)

Insulated stove will also cool exponentially:

$T_{iw} = C_1 e^{ct}$

$C_1 = 1200$ $C = -0.29$

$T_{ow} = C_1 e^{ct}$

$C_1 = 745$ $C = -0.24$

Insulated stove will cool down:

$$(Q/A)_{fire} = \underbrace{\sigma\,(\varepsilon_{fire}\,T_{fire}^{4}) - \alpha_{fire}\,T_{iw}^{4})}_{\text{term 1}} + \underbrace{\bar{h}_c\,(T_{fire} - T_{iw})}_{\text{term 2}} + \underbrace{\rho ct(T_{av1} - T_{av2})}_{\text{term 3}}$$

$$(Q/A)_{wall} = \frac{T_{iw} - T_{ow}}{(t/k)_{iw} + (t/k)_{ow}}$$

$$(Q/A)_{room} = \underbrace{\sigma\varepsilon\,(T_{ow}^{4} - T_{room}^{4})}_{\text{term 1}} + \underbrace{\bar{h}_c\,(T_{ow} - T_{room})}_{\text{term 2}}$$

at $t = 1$, $T_{fire} = 1347°F$ $(.11 = \varepsilon_{fire})$

$(Q/A)_{room}$				T_{iw}	α_{fire}	$(Q/A)_{fire}$				
T_{ow}	term 1	+ term 2	= total			term 1	+ term 2	+ term 3	= total	
400	709	+ 680	= 1389	564	0.15	1724	+ 1566	+ 925	= 4215	
600	1780	+ 1080	= 2860	938	0.14	1091	+ 818	+ 370	= 2279	
580	1641	+ 1040	= 2681	896	0.14	1195	+ 902	+ 429	= 2526	
575	1608	+ 1030	= 2638	886		1220	+ 922	+ 444	= 2586	
570	1575	+ 1020	= 2595	876		1243	+ 942	+ 459	= 2644	
at $t = 2$, $T_{fire} = 1029 (0.14 = \varepsilon_{fire})$										
420	788	+ 720	= 1508	598	0.15	855	+ 862	+ 414	= 2131	
450	917	+ 780	= 1697	650		787	+ 758	+ 335	= 1880	
470	1010	+ 820	= 1830	686		734	+ 686	+ 281	= 1700	
465	986	+ 810	= 1796	677		748	+ 704	+ 294	= 1746	
at $t = 3$, $T_{fire} = 785 (0.15 = \varepsilon_{fire})$										
370	600	+ 620	= 1220	514	0.15	385	+ 542	+ 250	= 1177	
365	584	+ 610	= 1194	506		393	+ 558	+ 262	= 1213	
at $t = 4$, $T_{fire} = 599°F (0.15)$										
270	316	+ 420	= 736	357	0.16	201	+ 484	+ 236	= 921	
280	339	+ 440	= 779	372		192	+ 454	+ 212	= 858	
275	327	+ 430	= 757	364		196	+ 470	+ 224	= 890	
285	351	+ 450	= 801	380		187	+ 438	+ 199	= 824	
290	365	+ 460	= 824	387		182	+ 424	+ 188	= 794	